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Performance Evaluation of the Russian SPT–100 Thruster at NASA LeRC

John M. Sankovic, John A. Hamley, and Thomas W. Haag
Lewis Research Center
Cleveland, Ohio

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PERFORMANCE EVALUATION OF THE RUSSIAN SPT-100 THRUSTER AT NASA LeRC

John M. Sankovic*, John A. Hamley**, and Thomas W. Haag†
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

Performance measurements of a Russian flight-model SPT-100 thruster were obtained as part of a comprehensive program to evaluate engineering issues pertinent to integration with Western spacecraft. Power processing was provided by a US Government developed laboratory power conditioner. When received the thruster had been subjected to only a few hours of acceptance testing by the manufacturer. Accumulated operating time during this study totaled 148 h and included operation of both cathodes. Cathode flow fraction was controlled both manually and using the flow splitter contained within the supplied xenon flow controller. Data were obtained at currrent levels ranging from 3 A to 5 A and thruster voltages ranging from 200 V to 300 V. Testing centered on the design power of 1.35 kW with a discharge current of 4.5 A. The effects of facility pressure on thruster operation were examined by varying the pressure via injection of xenon into the vacuum chamber. The facility pressure had a significant effect on thruster performance and stability at the conditions tested. Periods of current instabilities were noted throughout the testing period and became more frequent as testing progressed. Performance during periods of stability agreed with previous data obtained in Russian laboratories.

INTRODUCTION

The relatively recent availablity of the Russian Stationary Plasma Thruster (SPT) as a propulsion source for Western spacecraft has generated a great deal of interest in the device. The Ballistic Missile Defense Organization, BMDO, (formerly, Strategic Defense Initiative Organization) has been in the forefront of enabling the transfer of the technology to the US. In 1991, under BMDO sponsorship, a team of electric propulsion specialists from three government facilities evaluated the performance of the SPT-100 at two Russian test facilities.[1] That phase of the program documented the performance of the device and led the BMDO to support the acquisition of a thruster for continued life and performance testing in US laboratories, with the eventual program goal of flying SPT thrusters on the TOPAZ mission.

Concurrently, US commercial spacecraft manufacturers also began gaining interest in the device. The Space Systems Division of Loral (SS/L) had been investigating the feasibility similar devices for stationkeeping of geostationary satellites when the SPT became available.[2] A consortium, including SS/L, the Russian thruster manufacturer Fakel, and the Research Institute of Applied Mechanics and Electrodynamics (RIAME) of Moscow Aviation Institute, is currently marketing a SPT-100 system. The group is designing a new power processing unit and insuring flight qualification of the system to US standards.[3]

Under BMDO sponsorship, SPT testing is presently being conducted at the Jet Propulsion Laboratory and NASA's Lewis Research Center. The Jet Propulsion Laboratory is performing a cyclic life evaluation and an independent confirmation of the performance results.[4] The NASA Lewis Research Center's program is targeted at using its electric propulsion facilities to address broadbased engineering issues of concern to US industry and government agencies interested in using Russian technology. The program is similar to that conducted for the low-power hydrazine arcjet.[5,6] Under its program, NASA LeRC has developed and integrated a breadboard power processor to enable independent testing of the SPT-100.[7] Spacecraft contamination issues are being addressed through direct measurement of erosion/deposition on samples placed in the plume.[8] Optical diagnostics are being employed to identify the plume signature, in order to determine if spacecraft instrumentation such as star trackers will be affected.[9] Communications impacts due

*Aerospace Engineer, On-Board Propulsion Branch, Member AIAA
**Electrical Engineer, On-Board Propulsion Branch
†Aerospace Engineer, On-Board Propulsion Branch

to the plasma plume are being analyzed by the determination of the electron number density and temperature throughout the plume, thus allowing current computer models to be used to calculate any effect on the signal.[10] Radiated electromagnetic interference (EMI) from the thruster has been measured using eight antennas spanning the frequency range of 14 kHz-40 GHz.[11] Finally, high-fidelity performance measurements have been obtained using direct thrust measurements to assess facility impacts.

This paper summarizes the testing conducted to date with a Russian SPT-100 thruster at NASA LeRC. The performance evaluation concentrated on the design point condition of 300 V and 4.5 A using xenon as the propellant. Some parametric testing was performed by varying the current from 3 A to 5 A and the discharge voltage from 200 V to 300 V. The effects of facility pressure on thruster operation were investigated by independent injection of xenon and nitrogen into the facility. Start-up phenomena and the operation of the thruster over time are discussed. Also included are discussions on the instabilites encountered and the operating envelope of the device.

EXPERIMENTAL APPARATUS

THRUSTER

All testing was performed on a single SPT-100 thruster S/N 002 provided by the BMDO. The thruster is designed to operate with a discharge current of 4.5 A and a discharge voltage of 300 V. A description of the thruster operating principles is provided by Brophy, *et al.*[1], and a comprehensive review of closed-drift thruster technology is provided by Kaufman.[12] The thruster was manufactured by Fakel Enterprise in Kaliningrad, Russia. The SPT-100 was essentially new and had undergone only initial performance testing at the manufacturer. After initial check-out, the thruster insulator was cleaned by the manufacturer, as was customary before delivery. A photograph of the thruster in as received condition is provided in Figure 1. The thruster was supplied with two cathodes, with only one required for operation.

POWER PROCESSOR

All testing reported herein was performed using the NASA LeRC breadboard power processor (PPU). The power processor is described in detail in Ref. 7. The unit consisted of three power supplies. The discharge supply consisted of a phase-shifted, full bridge, pulse-width-modulated converter and its design relied heavily on the LeRC heritage in arcjet power processor development. It was designed to operate at 300 VDC output at 1.35 kW, but demonstrated operation down to 200 V and current levels between 3 A and 5 A. The heater supply provided 12 A to the cathode heater and used a push-pull topology. The ignitor circuit was based on arcjet ignition circuitry, and provided a 350 V pulse train to ignite the discharge. The PPU was designed for laboratory testing of the SPT. Consequently, a 120 V input voltage was selected to eliminate large step-up voltage requirements on the discharge transformer and to utilize cathode heater technology developed for the Space Station Freedom Plasma Contactor program. Since a complete description of the Russian flow control system was unavailable, automatic flow control was not incorporated in the PPU. A filter was incorporated in the PPU to prevent plasma instabilities from interacting with the power supply and is described in detail in Ref. 7.

FACILITY

All testing was conducted in one of two large vacuum facilities at NASA LeRC. The facilty is described in detail in Refs. 13 and 14. The vacuum chamber is 4.6 m in diameter and 19 m long. It contains twenty 0.8 m diameter oil diffusion pumps using silicon oil. The facility is also equipped with a helium cyropump system with an effective pumping area of 41 m^2. The helium surfaces are liquid nitrogen shrouded and can be cooled to 20 K with GHe and to 4.6 K with LHe. All tests in this facility were conducted using only the cyropanel operating on GHe. Pumping speeds for xenon were approximately 150,000 l/s and were determined using the thruster propellant flow rate and the pressure near the thruster. Diffusion pumps were unavailable at test time due to implementation of improvements to the freon cold traps. It is estimated that the diffusion pumps would add approximately 90,000 l/s xenon pumping. A schematic of the facility is provided in Figure 2. The facility is equipped with three gate-valved one meter diameter ports. Because of the large number of tests being conducted in the facility, common practice is to build-up the test articles on carts made to fit the ports, enabling quick turn around time between tests and eliminating the need to open the main chamber and cycle the cryosystem.

Thrust was measured directly using an inverted pendulum design thrust stand. The apparatus is described in detail in Ref. 15 and has been used for several years in testing low thrust propulsion devices. The particular thrust stand used in this study was previously used to measure the performance of US End-Hall thrusters described by Kaufman, *et al.*[2] The thrust stand was calibrated *in-situ* by loading it with three 39.2 mN (4.00 g) weights. The thrust stand was equipped with an inclinometer and a leveling motor to compensate for facility flexure after pumpdown and thermal distortions. Thermal loads from the thruster caused significant deflections in the test chamber and maintaining a constant reading on the inclinometer was found to be essential for precise thrust measurements. The uncertainty of the thrust measurements, determined by examination of the hysteresis and zero drift, was within ±1% of the reading.

The SPT was supplied with a Russian xenon flow controller (XFC). The device is mounted at the base of the thruster as shown in Figure 3. In typical operation the user supplies xenon through a single feedline. Exiting from the XFC are three propellant lines, one for each cathode and a single line for the anode. The cathode used depends on the valves energized in the XFC. The flow split between the cathode and anode is determined by an orifice in the propellant line. For this investigation, propellant was both injected directly into the anode and cathode via a by-pass of the XFC and also by using the XFC to determine the cathode/anode flow fraction. The XFC was by-passed by disconnecting the fittings downstream of the XFC and using adapter fittings specially made to fit the Russian thruster propellant connections and standard US gas fittings. Xenon was then injected independently into the cathode and anode. Flow control was initially provided by using fine metering valves connected to thermal-conductivity type flow meters. The flow meters were later replaced by flow controllers which used closed-loop control to automatically adjust an internal valve for flow regulation. The flow controllers had the advantage of being insensitive to feed pressure, unlike the flow meters. Both the flow meters and controllers were calibrated *in-situ* using a constant volume technique. A cylinder with known volume was evacuated and then filled for a known time period, once the flow had stabilized. By measuring the initial temperatures and pressures in the tank and using an equation of state, the flow rate could be determined. The accuracy of the technique was within ±1% due to uncertainties in the pressure, temperature, time, and volume measurements. The calibration technique was cross-checked with a bubble-meter technique and the NASA/LeRC Metrology Laboratory's mercury-sealed piston technique. The major uncertainites in the cathode flow came from the resolution of the flow meter equipment. Because of a large full-scale reading, cathode flow was known to ±4% at 0.05 cathode flow fractions. The cathode flow controller used to replace the meter in later testing had increased resoultion and significantly less uncertainty. Fittings employing metal-to-metal seals were used in the flow panel along with welded electropolished tubing for all sections of the gas system exposed to air. Hermetic integrity was checked by evacuating the line and using a helium detection system. The fittings immediately upstream of the thruster could not be checked in that manner since there was no way seal the cathodes or the anode. To check those fittings high purity nitrogen was passed through the thruster and the fittings were bubble checked. Xenon used as the propellant was 0.99999 pure.

INSTRUMENTATION

Electrical measurements were taken using isolated digital multimeters (DMM) with sense leads attached between the filter and the thruster at the vacuum feedthrough to the facility. The meters had an input impedance of nominally 10 megohms. Current was measured using the shunt internal to the DMM. Measurements were also obtained using a 1 GHz digital oscilloscope with 100:1 voltage probes to measure the discharge voltage. A Hall-effect current sensor, able to accurately measure currents from DC to 15 MHz, was used to measure discharge current. Meters were calibrated *in-situ* using a NIST traceable voltage and current calibration source. The digital oscilloscope software calculated the true-RMS of the signal. RMS readings from the oscilloscope were compared to the DMM's and agreed within ±0.05 A during all operating modes. Cathode-to-ground voltages, $V_{cath\text{-}gnd}$, were also measured using a DMM. It was found that during start-up when the cathode was being heated, a path to ground existed through the scope probes causing an erroneous reading. Once the discharge was ignited, the scope probes across the discharge had no effect on the $V_{cath\text{-}gnd}$ reading.

Facility pressures were measured using ionization gauges. When testing was conducted in the side port of the vacuum facility, the ionization gauge was located on the wall of the port, 0.6 m behind and 0.5 m above the centerline of the thruster exit plane. For the data taken in the center of the vacuum chamber, the ionization gauge was mounted on the thrust stand support structure, 0.7 m behind and 0.2 m from the thruster centerline. Interactions of the thruster plume with the ionization gauge were noted and necessitated the use of a ground screen across the opening of the gauge tube. The gauges were calibrated using air as a reference. All values reported were corrected for xenon, assuming the base pressure was caused by air. Corrections were accomplished by subtracting the operating pressure from the base pressure, dividing by a gas sensitivity factor[16], and then adding the base pressure.

EXPERIMENTAL PROCEDURE

The operating procedure supplied by the thruster manufacturer was used as the guideline during testing. Before testing the thruster was installed in the test facility and remained at vacuum level below 0.01 Pa (1 x 10^{-4} torr) for at least 16 h before testing. This was done in order to allow the thruster to outgas. Performance data were obtained with the thruster and thrust stand mounted in the one meter diameter test port (closest to end cap shown in Figure 2) and in the center of the vacuum chamber. For tests conducted inside the main chamber, the thrust stand was mounted in the center of the chamber 3.6 m from the mid-tank shield shown in Fig. 2. Half of the graphite louvers composing the mid-tank shield were removed, and the remainder were kept in the open position. The thruster and mounting structure were canted approximately 10° from the centerline so that the plume would pass through the open section of the mid-tank shield and impinge on the chamber wall near the cryopanel.

Upon initial installation in the center of the facility, even after 16 h at high vacuum, the thruster was still outgassing. This was determined through the use of three pressure gauges mounted throughout the facility. Two were mounted at opposite ends of the facility diagonally opposite each other on the facility walls. The third gauge was mounted on the thrust stand mounting structure. After every instance that the thruster was exposed to atmosphere, the highest pressure reading in the facility was at the thruster. After the thruster had been run, the static pressure was lowest at the thruster, followed by the gauge near the cryopanel. This is the facility pressure distribution expected if the thruster were no longer a source.

As mentioned previously, thrust stand calibration was performed *in-situ* by loading the thruster with calibrated weights. Calibration was performed before and after test runs. To investigate magnetic tares, 4 A of current was passed through the magnet while the thruster was mounted on the thrust stand, and no effect was noted. If shielding is not adequate, it is possible for the exhaust plasma in the vacuum chamber and EMI from the thruster to interact with the electronics of the thrust stand. To test for these effects, the thrust stand was loaded with a weight while the thruster was operating to make sure that the incremental deflection was the same as the one obtained with no discharge. This test was performed several times during the testing sequence and consistently showed the incremental deflections to be unaffected by the discharge. Different thrust values were obtained when the thruster entered episodes of instability characterized by large amplitude current oscillations. During these episodes an increased level of radiated EMI was measured.[11] It is plausible that the increased EMI could affect the thrust stand electronics and register a false decrease in thrust. Two tests were performed to ensure that the thrust measurement was not affected by EMI. First, the damping circuit was reversed, so that any disturbance of the thrust stand would now be amplified. That is in fact exactly what happened when the thruster entered an unstable mode, signaling that the thrust value had in fact changed. This alone did not prove that the thrust value in the unsteady mode was correct. A separate test was devised to determine EMI effects on thrust reading. The thruster leveling control was used to tilt the operating thruster so that the mount rested against a mechanical stop, essentially locking the thrust stand in one position. The stop was positioned to insure that the linear variable differential transformer of the thrust stand was still in a linear region. The thrust stand output with the thruster operating in a highly oscillatory mode was compared with the reading obtained when the discharge was off. The readings were found to be identical, demonstrating that thruster EMI did not affect the thrust stand signal.

All the data reported herein were obtained using a breadboard PPU which did not incorporate automatic flow control.[7] The supply provided a constant discharge voltage, and current was controlled by manually adjusting the propellant flow rate. Early in the test program, it was noted that upon initial start-up, the thruster usually entered a period instablity with large amplitude current oscillations. If the thruster were started at the flow rate required to obtain the steady state design point current of 4.5 A, current levels approaching 5 A were noted until the thruster stabilized. In order to prevent damage to the thruster electromagnet, the flow was reduced during start-up to approximately 4 mg/s. During the ignition sequence, propellant flow was initiated first. The discharge supply was then turned on, and a voltage of 300 V was established. The cathode heater was then turned on and supplied 12 A for 160 s. At that point the ignitor was turned on and a 350 V pulse train was used to ignite the discharge. Once the discharge was ignited the PPU automatically switched off the heater and pulser. If a difficulty was encountered during start-up, and the start was abandoned, twenty-five minutes elapsed before a another attempt was made. As specified by the manufacturer, twenty-five minutes was also the minimum time between run cycles. Also, in order to prevent oxidation, the thruster was not exposed to air until it had cooled for a minimum of three hours at high vacuum.

The operating voltages reported herein are measured across the discharge supply shown in Figure 4 (taken from Ref. 7). The thruster voltage includes the potential drop through the electromagnet. This was done to correctly calculate thruster power consumption for efficiency calculations and is commonly called "discharge" voltage by the manufacturer.

RESULTS AND DISCUSSION

Because of the variety of test results obtained, the data are presented chronologically in this section. The testing was broken down into five segments as shown in Figure 5. A tabular summary of the SPT-100 testing is provided in Appendix A. By the end of this study, the thruster had accumulated a total of 148.1 h of operation. Cathode 1 was operated for 127.6 h with 42 cycles and Cathode 2 accumulated 20.5 h of operation over 10 cycles

Starting reliability was very high throughout the testing. The level of development of the starting procedure was clear. In general the cathodes started very easily as soon as the pulser was turned on. Starting difficulty was only encountered when the switch was made to the second cathode after extended operation with the first. The first ignition with that cathode required several start attempts. During subsequent ignitions the second cathode started as reliably as the first.

Another general observation was that the behavior of the thruster changed with time. The thruster had a large stability envelope during initial testing, but quickly began to develop periods of current instability. By the end of the 148 h of operation, the stability envelope had decreased, and at the design point of 4.5 A/300 V the thruster would alternate between stable and unstable operations at a frequency of several hertz.

TEST SEGMENT 1

The thruster was mounted in the one meter diameter test port and subjected to parametric testing at current levels between 3 A and 5 A and thruster voltages between 200 V and 300 V. During the parametric testing, the facility pressure ranged from 0.0015 to 0.0020 Pa (1.1 to 1.5 x 10^{-5} torr). Because information on the Russian XFC was unavailable at this point, the propellant was supplied to the anode and cathode separately through manual flow control. The goal of the first set of tests, constituting a total run time of 19.4 h with ten starts, was to gain familiarity with the thruster. During this test series the effects of facility pressure on thruster performance were investigated. Xenon injected at the vacuum chamber wall opposite the thruster, was used to increase the facility pressure. Initial test results were significantly different than expected based on Russian acceptance test data. A propellant leak at the thruster which could not be vacuum-leak-checked was suspected. The connections were inspected and reassembled. Subsequent testing revealed a current/flow relationship closer to those reported previously, and the data from the final 7.6 h of testing in Segment 1 are discussed in the following paragraphs.

Performance data concentrated on the thruster design point of 4.5 A and 300 V. Typical operating behavior during start-up was characterized by a brief period of current oscillation and elevated mean current level. Typically the mean current level would decrease and the oscillations would disappear after a few minutes of operation. A sample of this behavior is provided in Figure 6. In that instance the thruster was operated at constant anode and cathode flow rates of 4.9 mg/s and 0.25 mg/s, respectively. A few seconds after ignition, the discharge current was 4.72 A with large amplitude oscillations, as shown in Figure 6a. Three minutes later, the oscillations damped out, and the current level dropped to 4.38 A as shown in Figure 6b. Twenty minutes after ignition the current had settled at a stable 4.31 A.

Table I shows a stability envelope of the thruster during initial performance testing. Testing at the design point conditions of 4.5 A and 300 V was performed at three different cathode flow rates ranging from 0.26 mg/s to 1.0 mg/s. Operation was generally similar except for short periods of instability at the highest cathode flow rate, as shown in Figure 7. The thruster was generally stable throughout the current range tested at cathode flow rates of 0.26 mg/s and 0.50 mg/s, with the exception of oscillations at 3 A. One cause of the lower stability at 3 A could have been the lower magnetic fields produced by lower currents passing through the electromagnets.

The cathode flow rate has a significant effect on the nature of the current instability. Using data taken at 3 A, Figure 8 shows that the frequency and the amplitude of the oscillations changed as the cathode flow fraction changed. For all three cathode flow rates the thruster voltage oscillations were minimal; however, both the specific impulse and efficiency were reduced when the oscillations occured, as noted by the data in Table II.

As in all electric propulsion devices the PPU is an inseparable part of the system. The current and voltages oscillations resulting from a plasma instability are coupled to the power processing electronics. The simplest way to eliminate the large current oscillations is to stop the plasma instabilities. Unfortunately, this may not be possible or practical. On the other hand, it may be possible to minimize their effect on performance through innovative filter and power processing controls. Recent tests with different filter designs have shown that the frequency of the oscillations can be changed by adding a resistor across the thruster electromagnet. It is not yet clear how that addition would effect the performance.

The effects of cathode flow rate on performance at current levels ranging between 3 A to 5 A with a constant thruster voltage of 300 V are provided in Figure 9 and Table II. At the design point of 4.5 A, performance at 0.26 mg/s and 0.50 mg/s cathode flow rates was essentially the same, giving a specific impulse of 1550 s and an efficiency of approximately 0.47. At the highest cathode flow rate of 1.0 mg/s the specific impulse decreased slightly. The off-design points show the same trend, except when an instablity occured. Operation in unstable regions caused steep drops in performance. An interesting occurence is that all the data, taken during both stable and unstable operation, fall on the same efficiency versus specific impulse curve as shown in Figure 9c.

The relationship between discharge current and anode flow rate at various cathode flow rates is shown in Figure 10 For all cases the relationship was very linear, and to achieve a given current level slightly less anode flow was required as cathode flow was increased.

Figure 11 shows the relationship between thrust and discharge current. Large decreases in thrust were noted during instability as is demonstrated by the 0.26 mg/s /3A point and the 1.0 mg/s /3.75,4.0,4.25 A points.

The effect of thruster voltage on performance was also investigated at current levels ranging from 3A to 5A. The data for voltages of 200 V and 250 V are provided in Table III, and the 300 V data are given in Table II. At the design point current of 4.5 A specific impulse and efficiency had a very linear relationship with applied voltage over the 100 V variation.

In order to determine the effects of facility pressure on performance, xenon was bled into the facility to increase background pressure from 0.0016 to 0.0065 Pa (1.2 - 4.9 x 10^{-5} torr). The gas was injected at a location on the opposite side of the vacuum chamber from the thruster. As shown in Figure 12, when the pressure was increased with the propellant flow rate constant, the discharge current was initially unaffected and then exponentially increased and became unstable. To maintain a constant power of 1.35 kW as the facility pressure was increased, the anode flow was decreased. Since thrust is a function of current, and current was kept constant, as the pressure increased and the flow decreased, the indicated specific impulse and efficiency increased. This is shown graphically in Figures 13a and 13b. The thrust was relatively constant until instability occured, and a precipitous change in performance was noted. The numerical data are provided in Table IV. Backflow into the thruster, calculated assuming free molecular flow and using the area between the insulators, did not account for the change in performance with facility pressure. All data reported herein are as measured, neglecting backflow.

In the beginning of the test program it was unclear whether the cathode flow split in the device was 0.05 or 0.1. Initial discussions with Russian specialists[17] led to the understanding that the split was 0.05, and testing was emphasized at that flow split. Later discussions with the manufacturer's representative suggested the split to be closer to 0.1.[18] Attempts to repeat the results are discussed later in this section.

TEST SEGMENT 2

Thrust measurements were not taken during this test segment, since the primary objective was to obtain data on the plume characteristics. After initial performance testing in the side port the thruster was placed in the center of the vacuum chamber. Operating pressures in the center of the chamber were approximately a factor of four lower than could be obtained in the side port. Quartz slides and plasma probes were positioned at two and four meter radii from the thruster to characterize deposition/erosion effects and plume plasma properties. The results from those tests are reported in Refs. 8 and 10. During those sets of tests, the thruster was operated for 58.2 h during 6 cycles, including a 50 h constant operating condition test. During the 50 h test the thruster anode flow was adjusted to achieve the design point condition of 4.5 A, and the cathode flow fraction was approximately 0.05 of the total. Thruster operation was similar to the results obtained in Segment 1. The current was stable during the test except for short "bursts" of instability. Typical operation during the test is shown in Figure 14a while two examples of the current instabilities noted are in Figures 14b and 14c. The "bursts" were very short duration, lasting only a few milliseconds. They occured in packets. Often ten to fifteen minutes would pass with no instabilities occuring then five to six would occur over the span of two minutes.

Post-test examination of the thruster showed that both insulators had become noticeably chamfered, and the insulator surface upstream of the chamfer was quite discolored. The orginal whitish-grey surface had already changed to a brown color during performance testing in Segment 1. After the plume characterization testing in Segment 2, the quantity of brown deposited material had increased. Also, the material was beginning to spall at the downstream edge, revealing the white insulator underneath, as shown in Figure 15. It is likely that the deposits in the acceleration channel were from the thruster itself, since other thruster surfaces, including the front face, were not coated.

TEST SEGMENT 3

To further examine facility pressure effects, the thrust stand was moved to the center of the vacuum chamber. A photograph of the set-up is provided as Figure 16. Facility issues limited test time to 4.4 h in the center of the chamber; however, facility pressures down to 0.0004 Pa (3×10^{-6} torr) were achieved during thruster operation at the design point. Table V contains the data obtained.

At the lowest facility pressure of 0.00043 Pa (3.2×10^{-6} torr), the specific impulse and efficiency at the design point were 1610 s and 0.50, respectively. The values are slightly higher than those obtained in the intial performance testing but are in agreement, considering experimental errors and the slight differences observed in cycle to cycle operation throughout the test sequence.

Some data were obtained at elevated facility pressures with the thruster operating at a 0.03 cathode flow fraction. The data show the same trend mentioned earlier. Facility issues did not allow further investigation of the performance/facility pressure phenomenon.

Following the mid-tank tests, BMDO sponsored Russian specialists from Fakel and MAI visited LeRC to observe the testing. The remainder of the testing during this segment was completed in the side port. At this point, the Fakel representative noted that the cathode flow fraction in the flight system was nearer to 0.1, rather than the 0.05 previously assumed.[18] During this test segment, the effect of cathode flow fraction on performance was studied. Results shown in Figures 17 and 18 indicate that the performance is strongly affected by cathode fractions below 0.04 and above 0.10. Within that range, the specific impulse and efficiency were essentially constant at 1600 s and 0.49, respectively . In tests using a cathode flow fraction of 0.07, the facility pressure was again elevated by injection of xenon into the main chamber. A slight increase in current level at constant propellant flow rate was noted, similar to the effect mentioned in Segment 1. However, the current instabilities occured at lower facility pressures, hampering attempts to obtain further data regarding the pressure/performance effect. The data are included in Table VI.

During the next set of tests the thruster was operated for approximately 1 h using a commercially developed PPU as part of a cooperative agreement.

To alleviate concerns that the observed facility effects were related to flow split, a series of tests were performed using the Russian XFC. The use of the XFC prevented the actual cathode flow rate from being measured and only the total propellant flow rate was known. The LeRC PPU was used for the tests and did not provided control of the thermal throttle valves in the XFC. The main valves and thermal throttles in the XFC were fully opened. Propellant control was provided manually upstream of the XFC, with the XFC serving solely as a flow splitter. The thruster was operated for 5.8 h and would not stabilize at the design point. It jumped between stable and unstable modes at a rate too rapid to obtain an accurate thrust reading. Operation in a totally oscillatory mode would be seen by the thrust stand as a constant thrust; however, changes in thrust due to switching between the two modes were quicker than the damper could compensate and caused an erratic reading. Stability was attained at 4 A discharge current, but once the flow was increased to attain 4.5 A, the thruster again became unsteady.

The plume intensity visually increased when in entered the unstable mode. The fluctuations between the modes, since they had a frequency on the order of hertz, were easily noted by the eye. The increased plume intensity episodes were quantified in Reference 9. Another interesting observance was that the interface on the insulator between the white, newly eroded insulator and the brown film covered section would glow orange during operation. Occasionally, the glowing material would be expelled, and a current transient would be noted on the oscilloscope.

In summary, the performance data obtained at the lowest faciilty pressure of 0.00043 Pa in the center of the vacuum facility with the thruster operating at its design point agreed with the advertised performance of 1600 s specific impulse with an efficiency of 0.5.[17] Elevated facility pressures were noted to affect the performance; however, the increased occurrence of current oscillations and problems with the test facility prevented a complete investigation of the phenomenon during this test segment.

TEST SEGMENT 4

The next battery of tests were conducted in the center of the vacuum facility to determine the radiated EMI from the thruster over the frequency range of 14 kHz to 40 GHz. Data were obtained during 23.7 h/ 7 cycles of thruster operation, and the XFC was used to provided the flow split. Unlike the testing in the side port at the end of Segment 3, thruster operation was steady at the design point after some initial periods of instability damped out. Testing was conducted mainly at the design point conditions. By injecting xenon into the chamber, EMI data were also obtained at various facility pressures. As the pressure was increased, the thruster again entered a current instability mode, but returned to stable operation once the bleed gas was turned off.

TEST SEGMENT 5

After EMI measurements were obtained, the thruster was again moved to the side port to obtain performance measurements with the XFC. The SPT was operated for 3 h and again experienced intermittent oscillations at the design point, preventing a thrust measurement. The operation was similar to the phenomena encountered in Segment 3, immediately before the EMI test sequence.

In order to evaluate the possibility of the oscillations being caused by the characteristics of the first cathode, the second cathode was wired into the PPU. Using the XFC, the thruster was operated with the second cathode for the first time for 3.8 h. Again, random jumps between stable and unstable operation prevented accurate thrust measurements.

The thruster was then moved into the center of the vacuum chamber to achieve lower operating pressures and to eliminate the possible of facility wall effects. The SPT was operated for 9.5 h with the XFC providing the flow split. At the design point the thruster again operated in both modes. This time the duration of operation was long enough to obtain a thrust reading at each level. Figure 19 shows a representative strip chart record of the thruster operation during this time period. Figure 20 provides oscilloscope traces showing operation in both stable and unstable modes. Performance during stable operation was similar to that obtained in Segment 3 without the XFC. At a facility pressure of 0.00050 Pa (3.8 x 10^{-6} torr), the specific impulse was 1590 s with an efficiency of 0.49.

For the last set of tests the XFC was by-passed and the flow to the anode and cathode was regulated manually. During the first 2.6 h of testing at cathode flow fractions between 0.05 and 0.1 the thruster experienced only brief periods of stability. During the succeeding 4.6 h of operation on the following day, the thruster would not stabilize and would alternate between modes with a frequency on the order of several hertz.

By the end of this test segment, the original thruster stability envelope shown in Table I had collapsed toward the design point. It is suspected that the coating on the insulator was playing a large role in thruster stability. It is recommended that during further testing, the brown film be cleaned off the insulators, to determine if stable operation can be restored.

CONCLUDING REMARKS

The object of this study was to understand the engineering and integration issues of the SPT-100 thruster. In doing so, the thruster has been treated as a "black box." The thruster was supplied by the BMDO and was subjected to five segments of testing over 148 h which included performance, plume characterization, and radiated EMI measurements. Performance evaluation was conducted both in a spool piece attached to the main chamber and in the center of the vacuum facility. All testing was performed using a US government designed PPU. Xenon flow control was provided manually and the cathode flow fraction was controlled both by using direct injection into the cathode and by allowing the Russian-supplied XFC to provide the flow split.

The robustness of the thruster system was demonstrated by reliable starting throughout the entire test program. During stable operation, performance data obtained at the lowest operating pressure of 0.0004 Pa (3 x 10^{-6} torr) showed a specific impulse of 1600 s at an efficiency of 0.50.

The stability envelope of the thruster drastically decreased over the course of operation. It is not clear how the insulator coating affects stability. The deposition phenomena and cause of the spalling are unknown. It is recommended that in future tests the insulator be cleaned to see if the original stability envelope will return.

Decreased performance was noted during periods of current instability. The interaction of the power processor with the dynamic impedance of the discharge has not been emphasized. Using innovative filter and power processing controls it may be possible to minimize the effect of the plasma instabilities on performance.

The thruster was sensitive to facility pressure at low cathode flow fractions. Attempts to repeat the data at cathode flow fractions near 0.1 were hampered by reduced stability as testing progressed. The exact cause of the phenomenon is unknown, and whether the pressure sensitivity varies with time also needs to be addressed.

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REFERENCES

1. Brophy, J.R., *et al.*, "Performance of the Stationary Plasma Thruster: SPT-100," AIAA-92-3155, July, 1992.

2. Kaufman, H.R., *et al.*, "End-Hall Thrusters," AIAA-90-2595, July, 1990.

3. Colbert, T., *et al.*, "Design of a High Efficiency Power Processor for the Russian Stationary Plasma Thruster," IEPC-93-043, *Proceedings of the 23rd International Electric Propulsion Conference*, September 1993, *to be published.*

4. Garner, C., *et al.*, "Performance Evaluation on Life Testing of the SPT-100," IEPC-93-091, *Proceedings of the 23rd International Electric Propulsion Conference*, September 1993, *to be published.*

5. Pencil, E.J., *et al.*, "Low Power Arcjet System Spacecraft Impacts," AIAA-93-2392, June 1993.

6. Morren, W.E. and Lichon, P.J., "Low-Power Arcjet Test Facility Impacts," AIAA-92-3532, July 1992.

7. Hamley, J.A., *et al.*, "Power Electronics Development for the SPT-100 Thruster," IEPC-93-044, *Proceedings of the 23rd International Electric*

Propulsion Conference, September 1993, *to be published.*

8. Pencil, E.J., "Far-Field Plume Sputtering Characterization of the Stationary Plasma Thruster (SPT-100)," IEPC-93-098, *Proceedings of the 23rd International Electric Propulsion Conference*, September 1993, *to be published.*

9. Manzella, D.A., "Stationary Plasma Thruster Plume Emissions," IEPC-93-097, *Proceedings of the 23rd International Electric Propulsion Conference*, September 1993, *to be published.*

10. Myers, R.M. and Manzella, D.A., "Stationary Plasma Thruster Plume Characteristics," IEPC-93-096, *Proceedings of the 23rd International Electric Propulsion Conference*, September 1993, *to be published.*

11. Sarmiento, C.J., Private Communication, NASA Lewis Research Center, July 1993.

12. Kaufman, H.R.,"Technology of Closed-Drift Thrusters," *AIAA Journal*, Vol. 23, No.1, pp. 78-87, January 1985.

13. Finke, R.C., *et al.*, "Space Environment Facility for Electric Propulsion Systems Research," NASA TN D-2774, May 1965.

14. Sovey, J.S., *et al.*, "Test Facilities for High Power Electric Propulsion," AIAA 91-3499, September 1991.

15. Haag, T.M. and Curran, F.M., "Arcjet Starting Reliability: A Multistart Test," AIAA 87-1061 (also NASA TM 89867), May 1987.

16. Holanda, R.,"Sensitivity of Hot-Cathode Ionization Vacuum Gages in Several Gases," NASA TN D-6815, July 1972.

17. Brophy, J.R., "Stationary Plasma Thruster Evaluation in Russia," JPL Publication 92-4, March 1992.

18. Grikhin, G.S., Private Communication, NASA Lewis Research Center, April 1993.

Table I. Thruster stability map during initial performance testing (Test Segment 1)

Table Ia. Cathode flow rate of 0.26 mg/s

		CURRENT, A				
		3.0	3.5	4.0	4.5	5.0
VOLTAGE, V	300	OSCILLATORY	STABLE	STABLE	STABLE	STABLE
	250	STABLE	STABLE	STABLE	STABLE	STABLE
	200	STABLE	STABLE	STABLE	STABLE	STABLE

Table Ib. Cathode flow rate of 0.50 mg/s

		CURRENT, A				
		3.0	3.5	4.0	4.5	5.0
VOLTAGE, V	300	BOTH MODES	STABLE	STABLE	STABLE	STABLE
	250	STABLE	STABLE	STABLE	STABLE	STABLE
	200	STABLE	STABLE	STABLE	STABLE	STABLE

Table Ic. Cathode flow rate of 1.0 mg/s

		CURRENT, A				
		3.0	3.5	4.0	4.5	5.0
VOLTAGE, V	300	OSCILLATORY	STABLE	OSCILLATORY	BOTH MODES	STABLE
	250	-	-	-	-	-
	200	-	-	-	-	-

Table II. Parametric performance data obtained at thruster design voltage of 300 V (Test Segment 1)

Voltage	Current	Power	Anode Flow	Cathode Flow	Total Flow	Cathode Fraction	Thrust	Specific Impulse	Efficiency	Facility Pressure
V	A	W	mg/s	mg/s	mg/s		mN	s		Pa
300.	3.01	903	3.45	0.26	3.71	0.071	44.3	1220	0.293	0.0014
300.	3.25	975	3.87	0.26	4.13	0.064	58.8	1450	0.430	0.0015
300.	3.51	1050	4.17	0.26	4.43	0.060	64.1	1480	0.441	0.0015
299.	3.75	1120	4.42	0.26	4.68	0.057	68.6	1490	0.448	0.0016
299.	3.97	1190	4.66	0.27	4.93	0.055	72.8	1510	0.453	0.0016
299.	4.25	1270	4.93	0.26	5.19	0.050	78.2	1540	0.464	0.0017
299.	4.50	1350	5.18	0.26	5.44	0.047	82.7	1550	0.467	0.0018
299.	4.75	1420	5.42	0.26	5.68	0.047	86.6	1550	0.464	0.0018
299.	4.98	1490	5.64	0.26	5.91	0.045	91.7	1580	0.478	0.0019
301.	4.27	1280	4.96	0.26	5.22	0.051	77.8	1520	0.452	0.0017
300.	3.01	904	3.55	0.50	4.05	0.12	54.5	1370	0.405	0.0014
300.	3.24	973	3.80	0.50	4.30	0.12	59.6	1410	0.425	0.0014
300.	3.49	1050	4.08	0.50	4.59	0.11	65.1	1450	0.441	0.0015
300.	3.75	1130	4.37	0.50	4.86	0.10	70.6	1480	0.455	0.0015
300.	4.08	1220	4.70	0.50	5.20	0.097	77.4	1520	0.470	0.0016
300.	4.50	1350	5.12	0.50	5.62	0.089	85.7	1550	0.484	0.0017
300.	5.00	1500	5.62	0.50	6.12	0.081	95.4	1590	0.496	0.0018
300.	4.08	1220	4.70	0.50	5.20	0.097	76.8	1510	0.464	0.0016
300.	3.00	901	3.35	1.0	4.38	0.24	52.5	1220	0.349	0.0015
300.	3.26	979	3.67	1.0	4.70	0.22	60.6	1310	0.399	0.0016
300.	3.48	1050	3.91	1.0	4.94	0.21	64.4	1330	0.401	0.0017
301.	3.77	1130	4.16	1.0	5.19	0.20	64.9	1270	0.358	0.0018
300.	4.00	1200	4.38	1.0	5.42	0.19	68.4	1290	0.359	0.0019
300.	4.24	1270	4.64	1.0	5.68	0.18	73.7	1320	0.375	0.0019
300.	4.50	1350	5.00	1.0	6.03	0.17	86.9	1470	0.463	0.0018
300.	4.75	1430	5.23	1.0	6.27	0.17	92.0	1500	0.474	0.0019
300.	4.98	1490	5.45	1.0	6.48	0.16	96.5	1520	0.481	0.0020
300.	3.72	1120	4.17	1.0	5.20	0.20	69.1	1350	0.411	0.0017

Table III Parametric performance data obtained at off-design thruster voltages (Test Segment 1)

Voltage	Current	Power	Anode Flow	Cathode Flow	Total Flow	Cathode Fraction	Thrust	Specific Impulse	Efficiency	Facility Pressure
V	A	W	mg/s	mg/s	mg/s		mN	s		Pa
250.	5.02	1260	5.55	0.26	5.82	0.045	76.0	1330	0.396	0.0021
250.	4.74	1190	5.30	0.26	5.57	0.047	72.8	1330	0.402	0.0020
250.	4.51	1130	5.10	0.26	5.37	0.049	70.0	1330	0.405	0.0019
250.	4.32	1080	4.94	0.26	5.21	0.051	68.1	1330	0.413	0.0018
250.	4.00	1000	4.64	0.26	4.91	0.054	64.0	1330	0.417	0.0018
250.	3.75	937	4.41	0.26	4.67	0.057	61.1	1330	0.426	0.0017
250.	3.50	874	4.17	0.26	4.43	0.060	57.4	1320	0.425	0.0016
250.	3.25	812	3.89	0.26	4.16	0.064	52.4	1290	0.406	0.0015
250.	2.98	744	3.61	0.26	3.87	0.068	47.5	1250	0.392	0.0015
250.	4.31	1080	4.93	0.26	5.20	0.051	67.4	1320	0.406	0.0019
250.	4.95	1240	5.53	0.50	6.03	0.083	83.7	1410	0.468	0.0020
250.	4.75	1190	5.35	0.50	5.86	0.086	80.2	1400	0.462	0.0019
250.	4.49	1120	5.12	0.50	5.62	0.089	76.2	1380	0.460	0.0019
250.	4.24	1060	4.87	0.50	5.37	0.094	72.2	1370	0.457	0.0018
250.	4.07	1020	4.71	0.50	5.20	0.095	68.7	1350	0.446	0.0018
250.	3.75	938	4.38	0.50	4.89	0.10	63.5	1330	0.441	0.0017
250.	3.50	874	4.12	0.50	4.63	0.11	59.1	1300	0.431	0.0016
250.	3.25	812	3.83	0.50	4.33	0.11	54.3	1280	0.420	0.0015
250.	3.01	752	3.58	0.50	4.07	0.12	50.0	1250	0.408	0.0015
250.	4.07	1020	4.71	0.50	5.21	0.10	69.0	1350	0.449	0.0018
201.	4.99	1000	5.51	0.26	5.78	0.046	62.5	1100	0.337	0.0022
201.	4.76	955	5.30	0.26	5.57	0.047	60.2	1100	0.341	0.0022
201.	4.50	903	5.05	0.26	5.31	0.049	58.4	1120	0.355	0.0021
201.	4.25	853	4.82	0.26	5.08	0.051	55.9	1120	0.362	0.0019
201.	4.01	805	4.59	0.26	4.86	0.054	53.1	1110	0.360	0.0019
201.	3.74	751	4.34	0.26	4.61	0.057	50.5	1120	0.368	0.0018
201.	3.48	698	4.11	0.26	4.37	0.060	47.1	1100	0.364	0.0017
201.	3.25	652	3.87	0.26	4.14	0.064	43.5	1070	0.351	0.0016
201.	2.98	598	3.61	0.26	3.87	0.068	40.0	1050	0.345	0.0015
201.	4.98	998	5.48	0.50	5.98	0.083	70.4	1200	0.416	0.0021
201.	4.73	948	5.25	0.50	5.74	0.086	67.3	1190	0.415	0.0020
201.	4.49	900	5.05	0.50	5.54	0.089	64.1	1180	0.412	0.0020
201.	4.24	851	4.81	0.50	5.31	0.093	60.7	1170	0.408	0.0019
201.	3.98	798	4.58	0.50	5.07	0.098	57.4	1150	0.407	0.0018
201.	3.75	752	4.36	0.50	4.85	0.10	54.2	1140	0.403	0.0018
201.	3.49	700	4.08	0.50	4.57	0.11	50.1	1120	0.393	0.0017
201.	3.25	652	3.83	0.50	4.33	0.11	46.5	1200	0.384	0.0016
201.	2.99	599	3.56	0.50	4.06	0.12	42.5	1070	0.371	0.0015

Table IV. Performance data showing effects of facility pressure (Test Segment 1)

Voltage	Current	Power	Anode Flow	Cathode Flow	Total Flow	Cathode Fraction	Thrust	Specific Impulse	Efficiency	Facility Pressure
V	A	W	mg/s	mg/s	mg/s		mN	s		Pa
300.	4.51	1350	5.14	0.26	5.40	0.048	81.6	1540	0.456	0.0016
300.	4.51	1350	5.13	0.26	5.39	0.048	85.2	1610	0.498	0.0030
300.	4.53	1360	5.13	0.26	5.39	0.048	86.2	1630	0.506	0.0036
300.	4.55	1370	5.13	0.26	5.39	0.048	87.0	1640	0.514	0.0041
300.	4.69	1410	5.13	0.26	5.38	0.048	90.5	1710	0.540	0.0057
301.	4.88	1470	5.13	0.26	5.38	0.048	80.1	1520	0.407	0.0065
301.	4.48	1350	4.71	0.26	4.97	0.052	73.8	1510	0.406	0.0065
300.	4.25	1280	4.95	0.26	5.21	0.050	77.5	1520	0.453	0.0017
300.	4.30	1290	4.94	0.26	5.20	0.050	78.0	1530	0.454	0.0024
300.	4.37	1310	4.94	0.26	5.20	0.050	81.4	1600	0.486	0.0030
300.	4.46	1340	4.94	0.26	5.20	0.050	80.8	1580	0.469	0.0039
300.	4.72	1420	4.93	0.26	5.19	0.050	84.3	1660	0.483	0.0057
300.	4.86	1460	4.93	0.26	5.19	0.050	85.8	1680	0.485	0.0065
300.	5.05	1520	4.93	0.26	5.19	0.050	87.6	1720	0.487	0.0078
300.	4.24	1270	4.93	0.26	5.19	0.050	76.8	1510	0.447	0.0017

Table V. Performance data obtained in center of vacuum facility (Test Segment 3)

Voltage	Current	Power	Anode Flow	Cathode Flow	Total Flow	Cathode Fraction	Thrust	Specific Impulse	Efficiency	Facility Pressure
V	A	W	mg/s	mg/s	mg/s		mN	s		Pa
301.	4.52	1360	5.09	0.15	5.23	0.028	72.6	1420	0.371	0.00044
301.	4.50	1350	5.12	0.15	5.26	0.028	77.5	1500	0.422	0.0016
301.	4.52	1360	5.12	0.15	5.26	0.028	79.5	1540	0.442	0.0026
300.	4.55	1370	5.12	0.15	5.26	0.028	81.0	1570	0.456	0.0033
300.	4.59	1380	5.12	0.15	5.26	0.028	82.8	1600	0.473	0.0041
300.	4.59	1380	5.04	0.15	5.19	0.028	84.3	1660	0.498	0.0056
300.	4.51	1350	4.98	0.15	5.13	0.028	82.7	1650	0.493	0.0052
300.	4.65	1400	5.12	0.15	5.27	0.028	85.7	1660	0.500	0.0052
300.	4.57	1370	5.11	0.15	5.25	0.028	73.9	1430	0.379	0.00043
301.	4.76	1430	5.15	0.15	5.30	0.029	72.6	1400	0.347	0.00045
301.	4.52	1360	4.94	0.15	5.09	0.030	69.2	1380	0.345	0.00042
301.	4.27	1290	4.72	0.15	4.87	0.031	63.8	1340	0.325	0.00041
301.	3.98	1200	4.46	0.15	4.61	0.033	61.5	1360	0.341	0.00041
301.	3.48	1050	3.99	0.15	4.14	0.037	56.8	1400	0.371	0.00038
300.	3.26	979	3.76	0.15	3.91	0.039	55.2	1440	0.397	0.00035
301.	2.99	899	3.46	0.15	3.61	0.042	51.6	1460	0.410	0.00033
301.	4.75	1430	5.25	0.38	5.63	0.067	90.1	1630	0.505	0.00045
301.	4.49	1350	4.99	0.38	5.37	0.070	84.9	1610	0.498	0.00043
301.	4.26	1280	4.76	0.38	5.13	0.073	80.0	1590	0.487	0.00042
301.	4.00	1200	4.52	0.38	4.90	0.077	75.1	1560	0.479	0.00040
301.	3.76	1130	4.25	0.38	4.62	0.081	70.1	1550	0.470	0.00039
301.	3.49	1050	3.95	0.38	4.33	0.087	64.4	1520	0.457	0.00037
301.	3.27	983	3.71	0.38	4.08	0.092	59.5	1490	0.441	0.00035

Table VI. Performance after 90 h of operation (Test Segment 3)

Voltage	Current	Power	Anode Flow	Cathode Flow	Total Flow	Cathode Fraction	Thrust	Specific Impulse	Efficiency	Facility Pressure
V	A	W	mg/s	mg/s	mg/s		mN	s		Pa
299.	4.51	1350	4.94	0.37	5.31	0.070	85.4	1640	0.508	0.0016
300.	4.54	1360	4.93	0.37	5.30	0.070	86.1	1660	0.515	0.0025
300.	4.55	1360	4.92	0.37	5.29	0.070	86.3	1660	0.516	0.0028
300.	4.58	1370	4.93	0.37	5.30	0.070	86.2	1660	0.512	0.0030
300.	4.57	1370	4.92	0.37	5.29	0.070	87.0	1680	0.523	0.0032
300.	4.60	1380	4.92	0.37	5.29	0.070	86.9	1670	0.518	0.0035
299.	4.76	1430	5.19	0.38	5.56	0.068	88.7	1630	0.497	0.0016
299.	4.46	1340	4.92	0.37	5.29	0.070	84.0	1620	0.500	0.0016
300.	4.00	1200	4.46	0.36	4.82	0.075	75.3	1590	0.490	0.0015
300.	3.50	1050	3.93	0.38	4.32	0.089	64.9	1530	0.465	0.0014
300.	3.23	969	3.52	0.38	3.90	0.098	50.2	1310	0.334	0.0014
300.	4.47	1340	4.92	0.38	5.29	0.071	84.0	1620	0.498	0.0016
300.	4.44	1330	4.92	0.15	5.07	0.030	72.2	1450	0.386	0.0017
299.	4.49	1340	4.97	0.22	5.20	0.043	81.3	1590	0.473	0.0016
299.	4.50	1350	4.97	0.29	5.26	0.055	83.5	1620	0.492	0.0016
300.	4.50	1350	4.96	0.38	5.33	0.070	83.8	1600	0.489	0.0016
299.	4.53	1360	4.97	0.44	5.41	0.082	85.2	1600	0.494	0.0016
300.	4.58	1370	4.96	0.68	5.65	0.12	86.8	1570	0.486	0.0016
300.	4.48	1340	4.86	0.69	5.55	0.12	84.5	1550	0.479	0.0016
300.	4.53	1360	4.85	0.88	5.72	0.15	84.2	1500	0.456	0.0017

Appendix A

Thruster Testing History

DATE	OPERATING TIME	CYCLES	FLOW SPLIT	CATHODE	TEST LOCATION	COMMENTS
2/12/93	268	3	XFC by-passed	1	1 m dia port	Performance testing Propellant leak suspected
2/17/93	375	3	XFC by-passed	1	1 m dia port	Performance testing Propellant leak suspected
2/18/93	238	2	XFC by-passed	1	1 m dia port	Performance testing Propellant leak suspected
2/19/93	281	2	XFC by-passed	1	1 m dia port	Performance testing Propellant leak suspected
2/25/93	383	2	XFC by-passed	1	1 m dia port	Performance testing
2/26/93	75	1	XFC by-passed	1	1 m dia port	Performance testing
3/10/93	167	2	XFC by-passed	1	1 m dia port	Performance testing
3/12/93	300	1	XFC by-passed	1	Tank center	Far field plume data using plasma probes and quartz slides
3/16/93-3/18/93	3023	3	XFC by-passed	1	Tank center	Far field plume data using plasma probes and quartz slides Single point operation
4/6/93	52	1	XFC by-passed	1	Tank center	Performance testing Instrumentation/Facility problems
4/7/93	73	2	XFC by-passed	1	Tank center	Performance testing
4/8/93	140	2	XFC by-passed	1	Tank center	Performance testing
4/27/93	272	3	XFC by-passed	1	1 m dia port	Performance testing
4/29/93	5	2	via XFC	1	1 m dia port	Testing with commercial PPU
4/30/93	57	2	via XFC	1	1 m dia port	Testing with commercial PPU
5/1/93	347	2	via XFC	1	1 m dia port	Performance testing Unstable at design point
5/7/93	262	3	via XFC	1	Tank center	Radiated EMI measurements
5/12/93	414	1	via XFC	1	Tank center	Radiated EMI measurements
5/13/93	160	1	via XFC	1	Tank center	Radiated EMI measurements
5/15/93	342	1	via XFC	1	Tank center	Radiated EMI measurements
5/18/93	246	1	via XFC	1	Tank center	Radiated EMI measurements
6/2/93	176	2	via XFC	1	1 m dia port	Performance measurements Alternated between stable operation and current oscillations at design point
6/8/93	230	2	via XFC	2	1 m dia port	Performance measurements Alternated between stable operation and current oscillations at design point
6/15/93	402	2	via XFC	2	Tank center	Performance measurements Alternated between stable operation and current oscillations at design point
6/16/93	167	3	via XFC	2	Tank center	Performance measurements Alternated between stable operation and current oscillations at design point
6/18/93	153	2	XFC by-passed	2	Tank center	Performance measurements Alternated between stable operation and current oscillations at design point
6/19/93	278	1	XFC by-passed	2	Tank center	Performance measurements Alternated between stable operation and current oscillations at design point

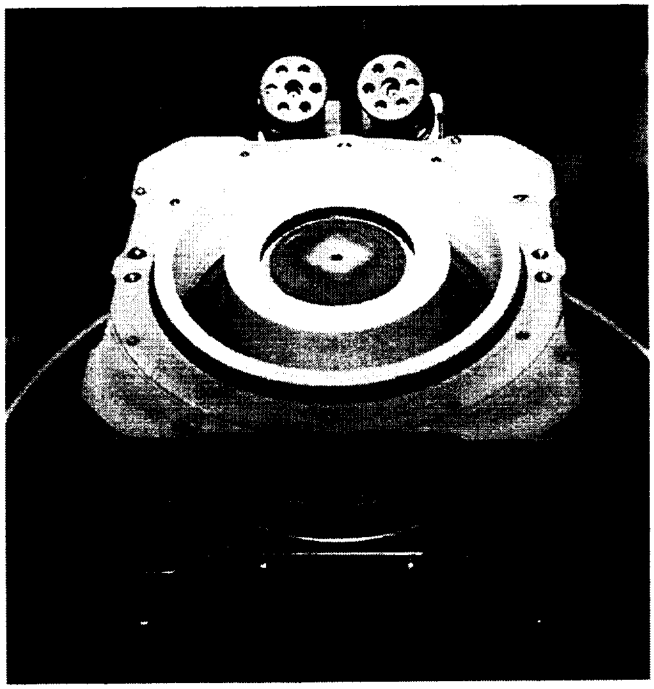


Figure 1.—SPT-100 thruster before operation at NASA Lewis Research Center.

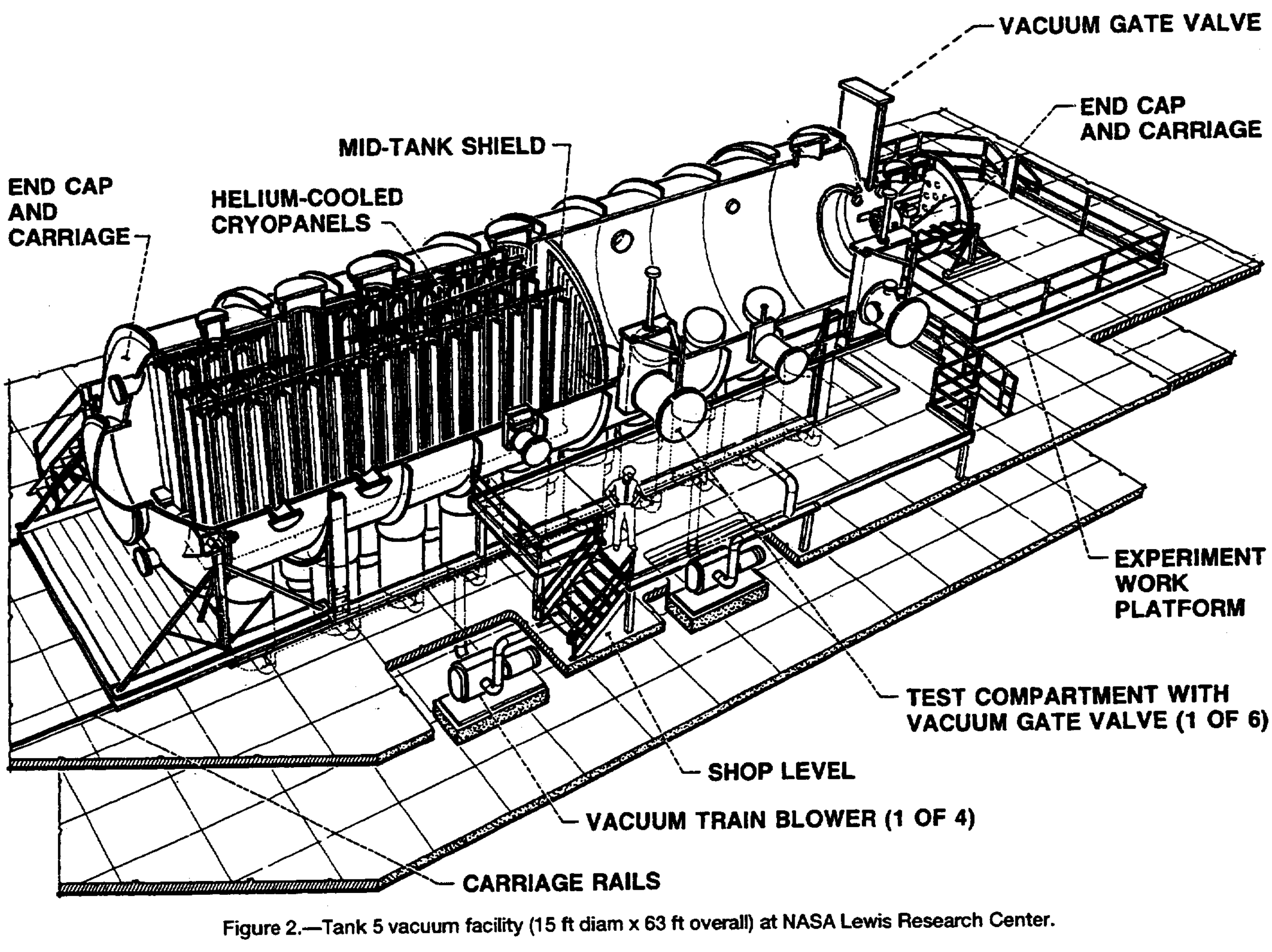


Figure 2.—Tank 5 vacuum facility (15 ft diam x 63 ft overall) at NASA Lewis Research Center.

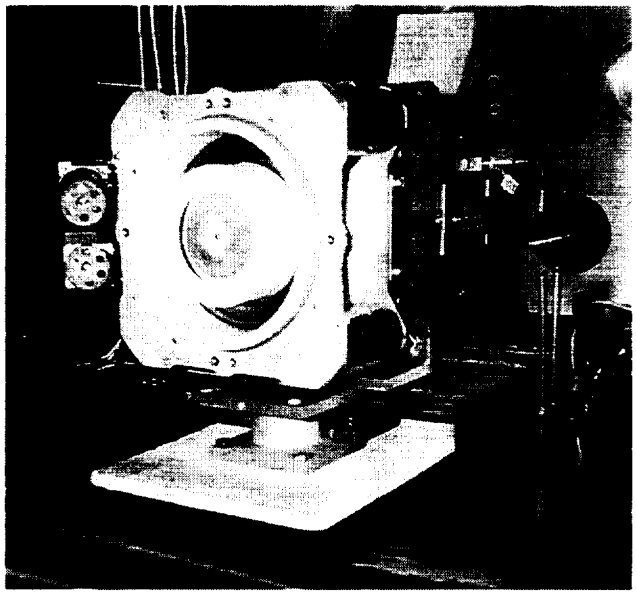


Figure 3.—SPT-100 thruster with xenon flow controller mounted directly behind thruster.

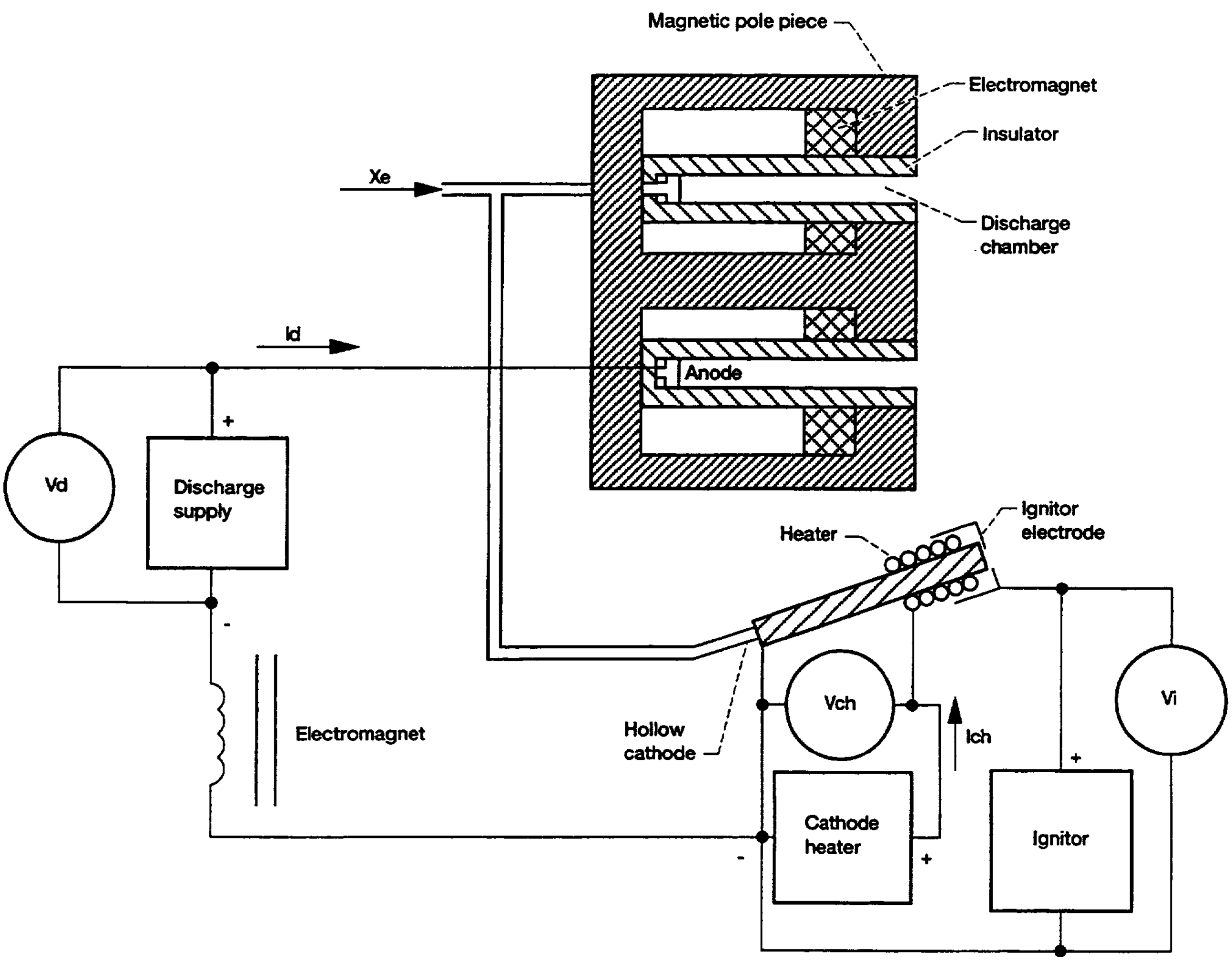


Figure 4.—Electrical schematic of test set-up. (From Ref. 7).

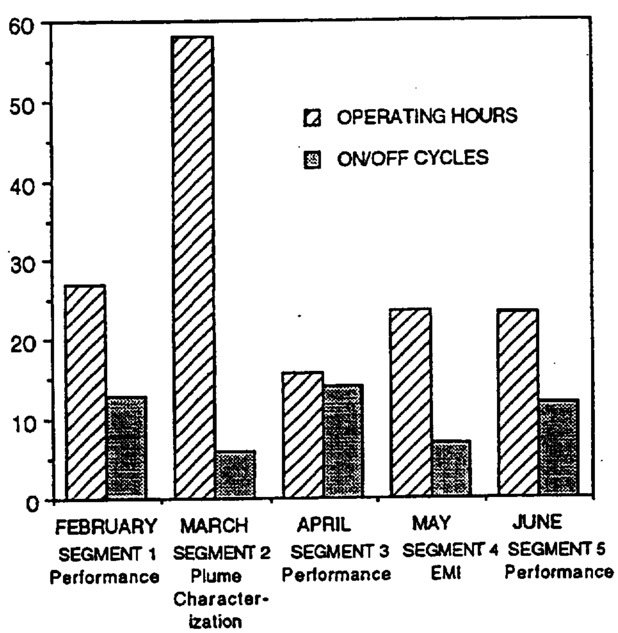


Figure 5.—Thruster operating time during the five test segments.

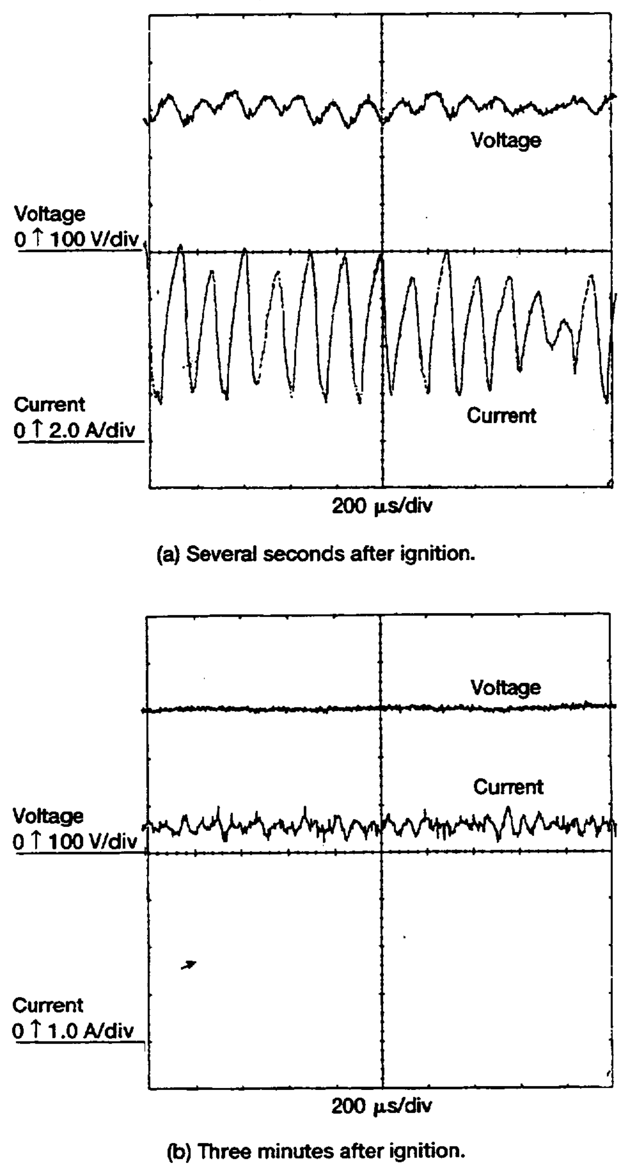
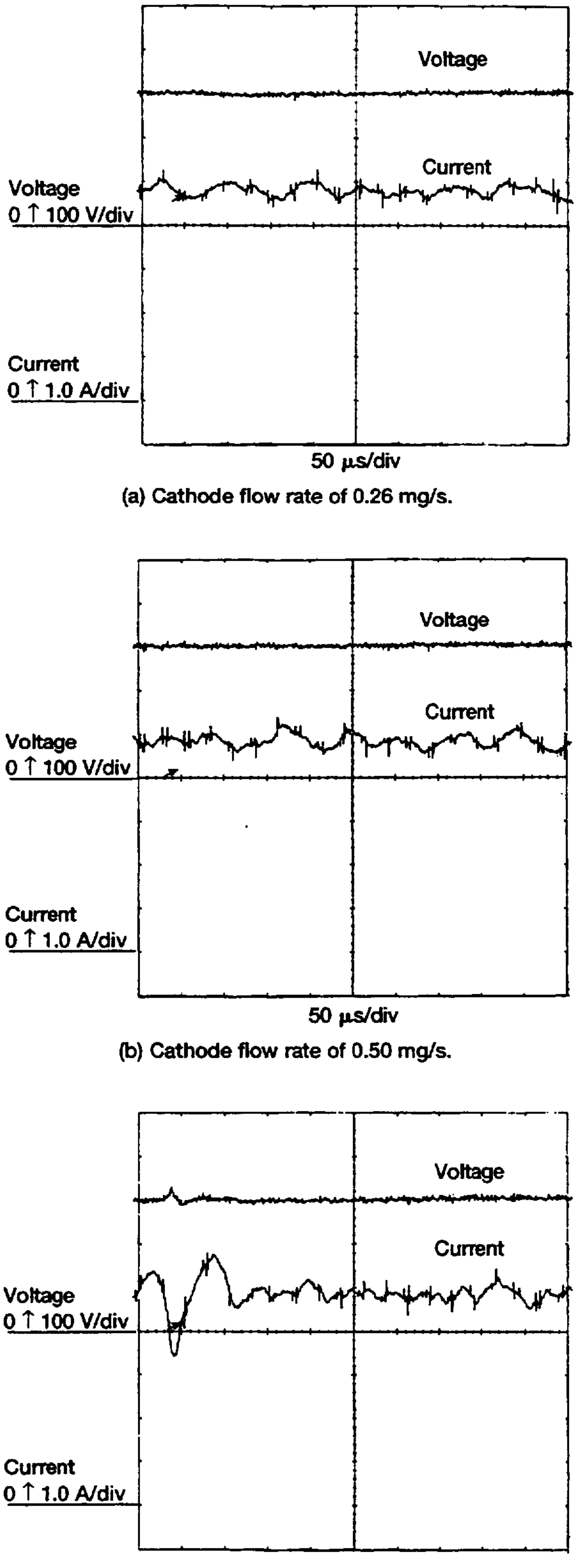


Figure 6.—Oscilloscope traces of thruster voltage and discharge current. (Test segment 1).

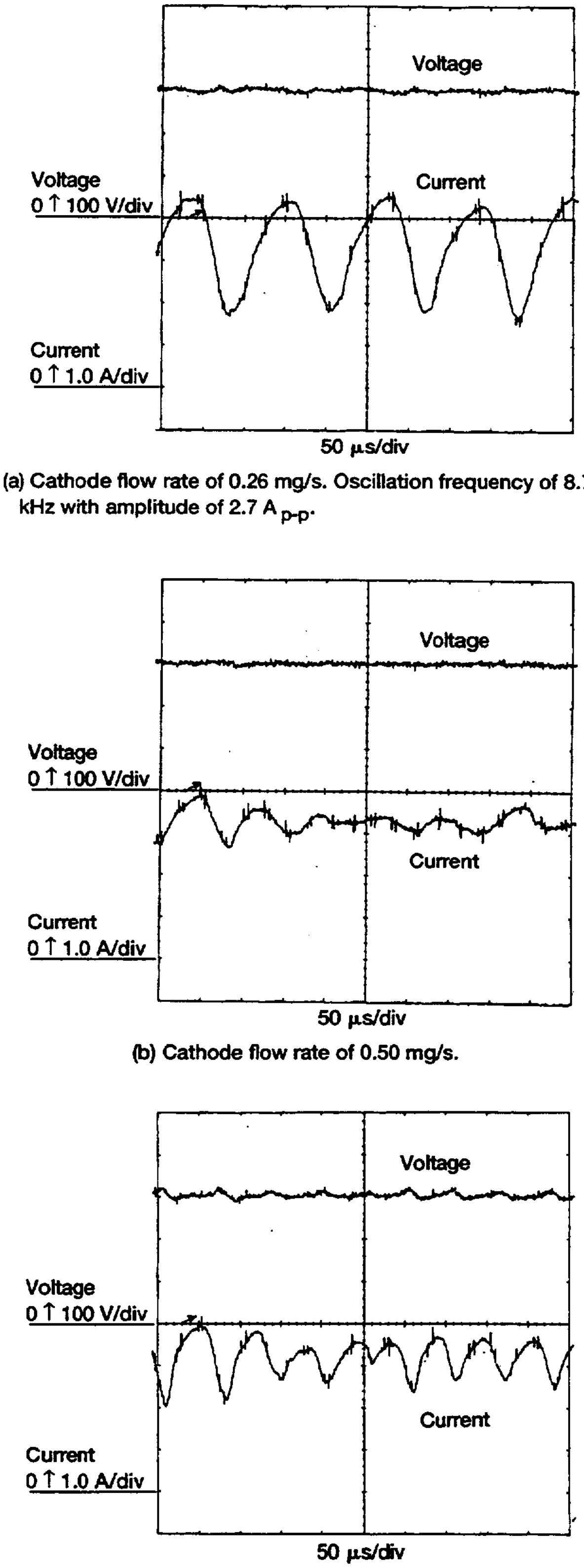


(a) Cathode flow rate of 0.26 mg/s.

(b) Cathode flow rate of 0.50 mg/s.

(c) Cathode flow rate of 1.0 mg/s.

Figure 7.—Oscilloscope traces of thruster voltage and discharge current at design point. (Test segment 1).

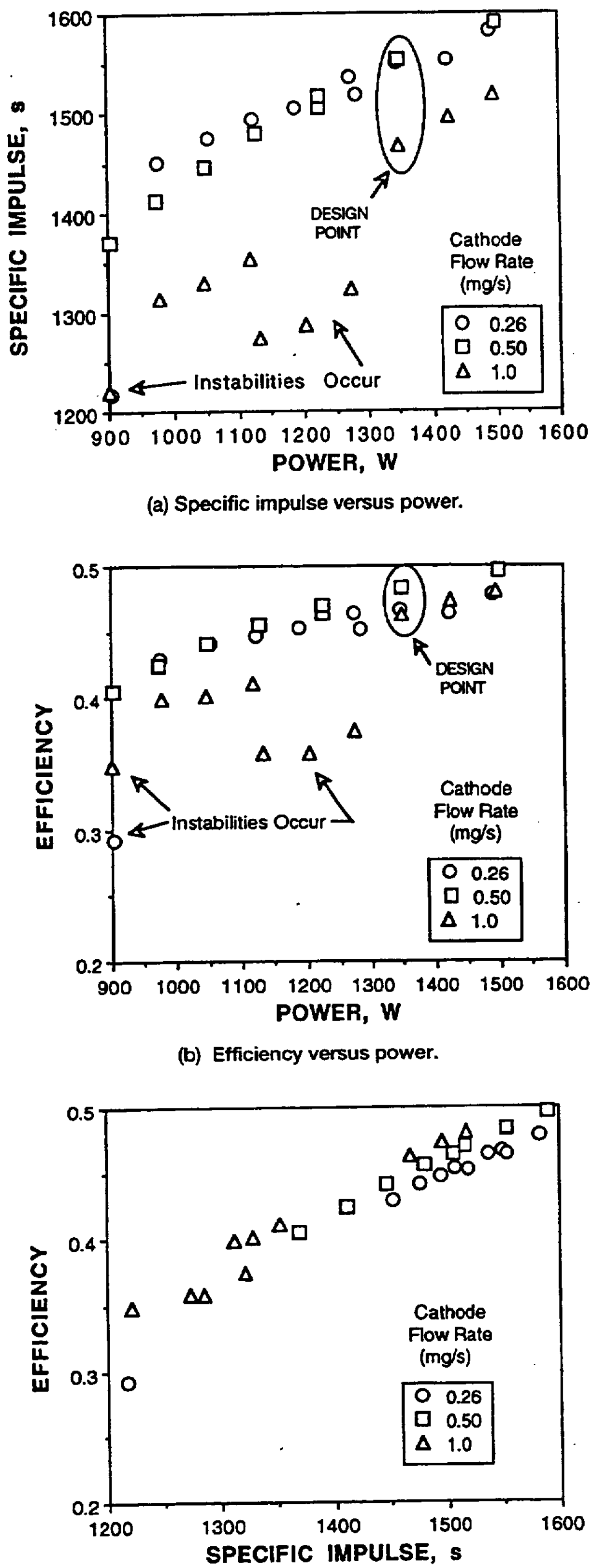


(a) Cathode flow rate of 0.26 mg/s. Oscillation frequency of 8.7 kHz with amplitude of 2.7 $A_{p\text{-}p}$.

(b) Cathode flow rate of 0.50 mg/s.

(c) Cathode flow rate of 1.0 mg/s. Oscillation frequency of 16.8 kHz with amplitude varying between 0.94 and 1.8 $A_{p\text{-}p}$.

Figure 8.—Oscilloscope traces of thruster voltage and discharge current at 300 V and 3.0 A. (Test segment 1).



(a) Specific impulse versus power.

(b) Efficiency versus power.

(c) Efficiency versus specific impulse.

Figure 9.—Effects of cathode flow rate on performance. (Test segment 1).

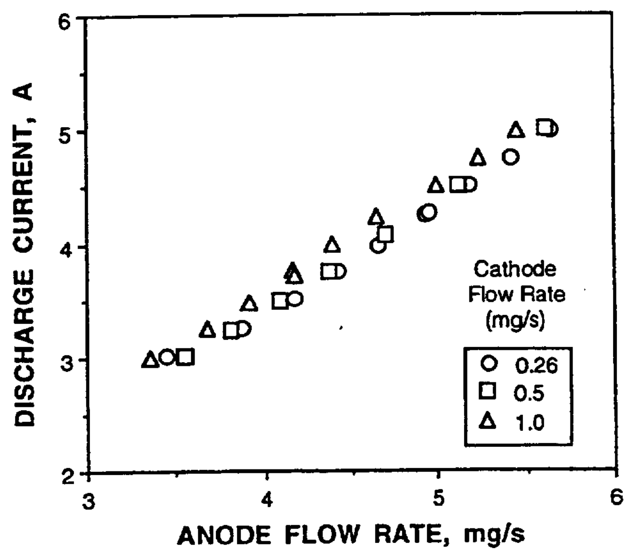


Figure 10.—Effect of anode flow rate on discharge current. (Test segment 1).

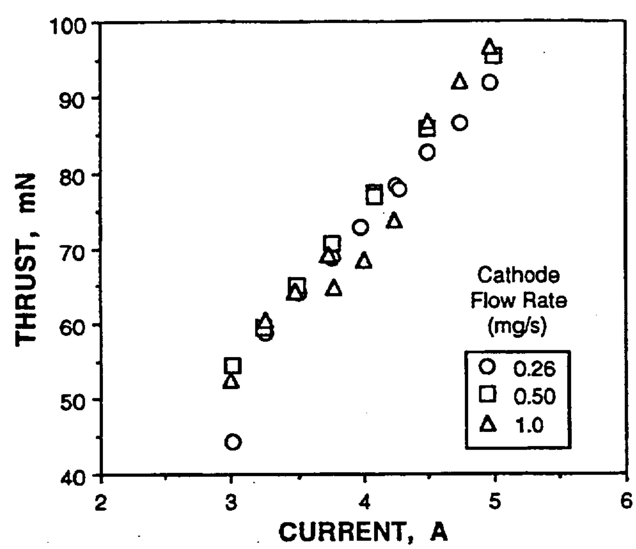
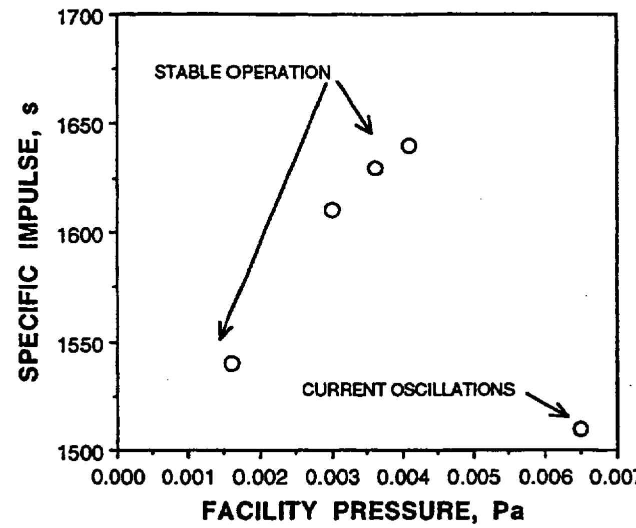


Figure 11.—Effect of discharge current on thrust. (Test segment 1).



(a) Specific impulse versus facility pressure.

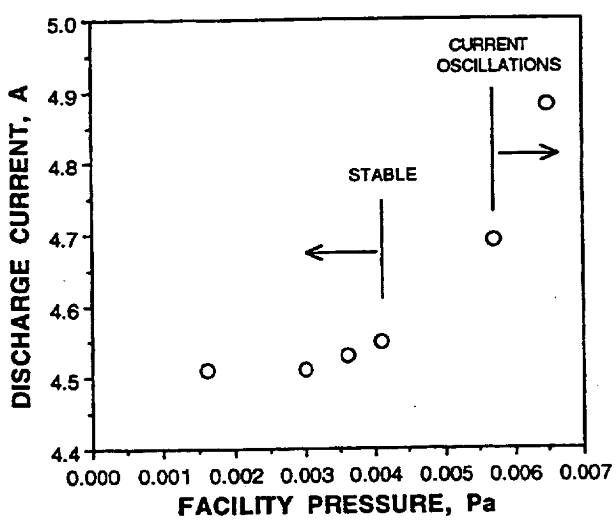
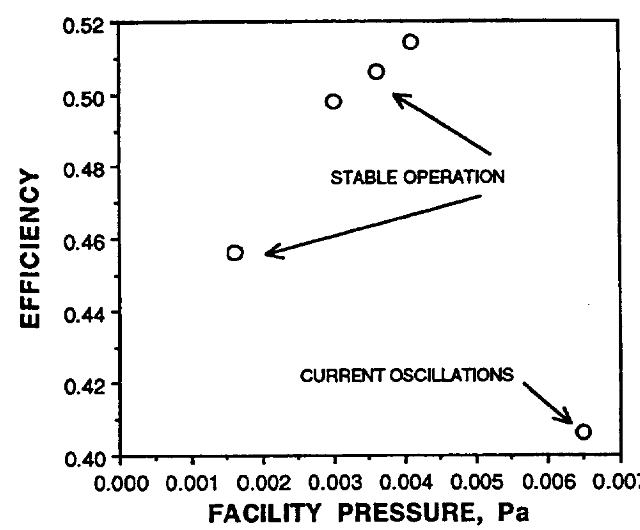


Figure 12.—Effect of facility pressure on discharge current. 300 V thruster voltage of 300 V and 0.26 mg/s cathode flow rate. (Test segment 1).



(b) Efficiency versus facility pressure.

Figure 13.—Effect of facility pressure on performance. Anode flow rate adjusted to maintain 4.5 A discharge current. Thruster voltage of 300 V and 0.26 mg/s cathode flow rate. (Test segment 1).

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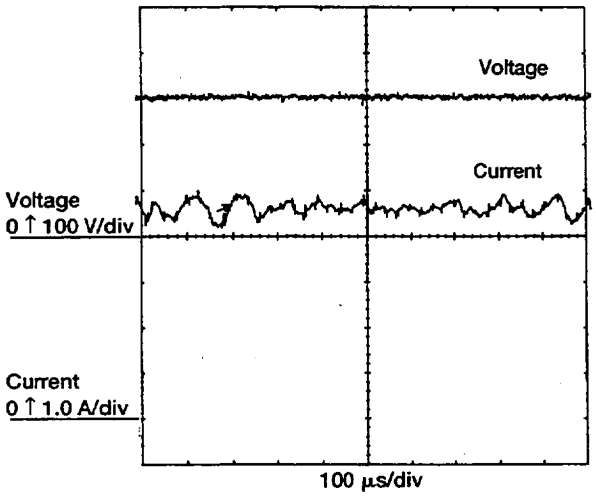
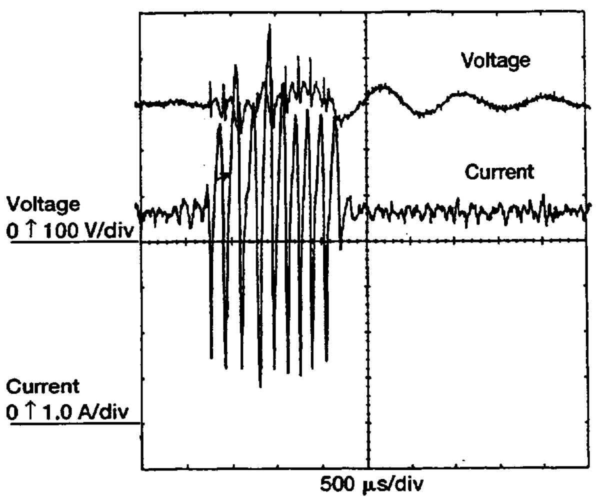
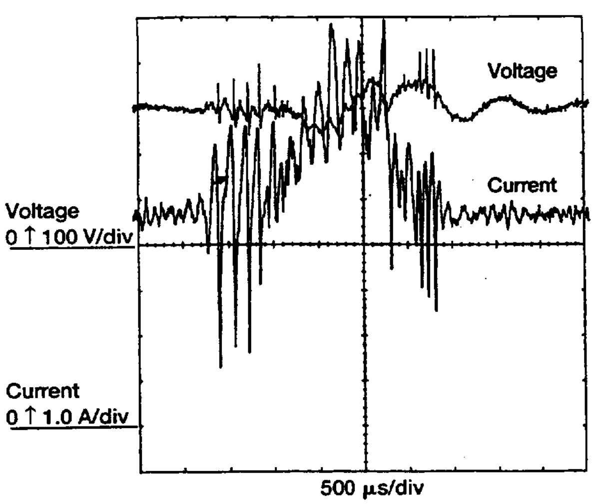


(a) Typical operation.



(b) Current instablility "burst".



(c) Current instability "burst".

Figure 14.—Oscilloscope traces showing thruster operation during 50h endurance test. (Test segment 2).

Figure 15.—Photograph showing thruster acceleration channel and spalling of brown coating on inner insulator. (Test segment 2).

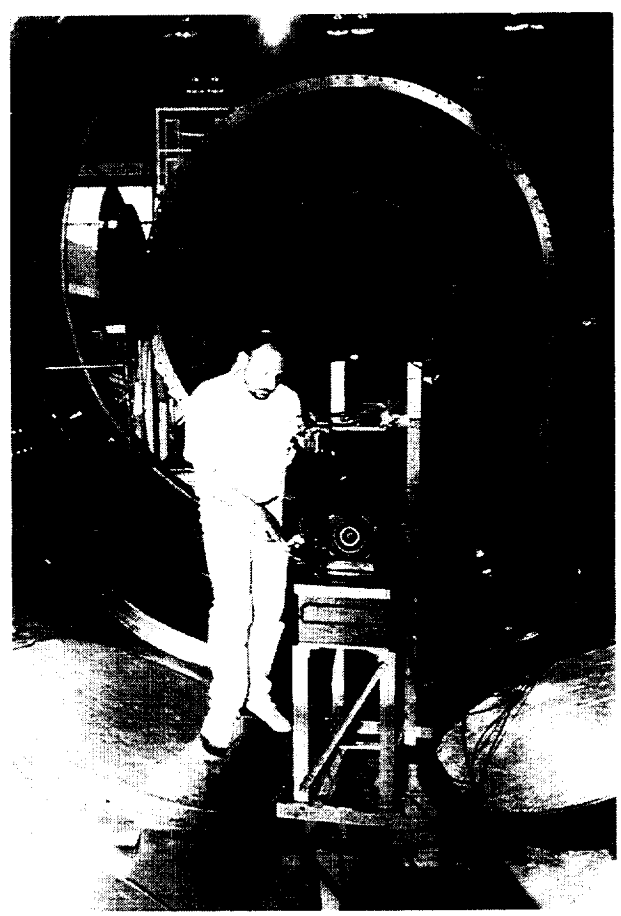


Figure 16.—Photograph showing SPT mounted on thrust stand in center of vacuum facility.

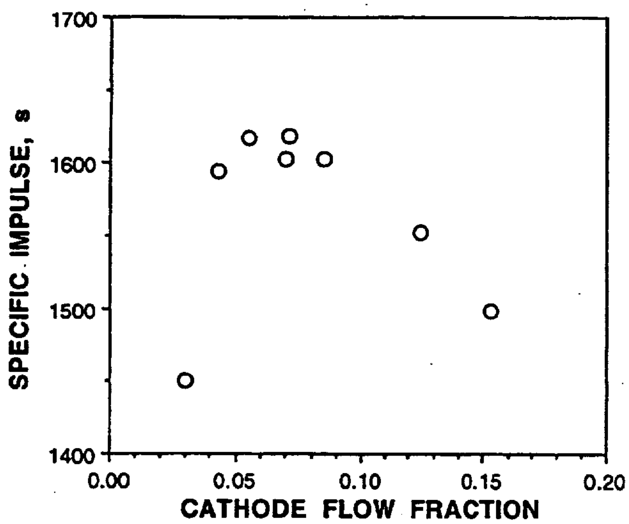


Figure 17.—Effect of cathode flow fraction on specific impulse. Thruster voltage of 300 V and discharge current of 4.5 A. (Test segment 3).

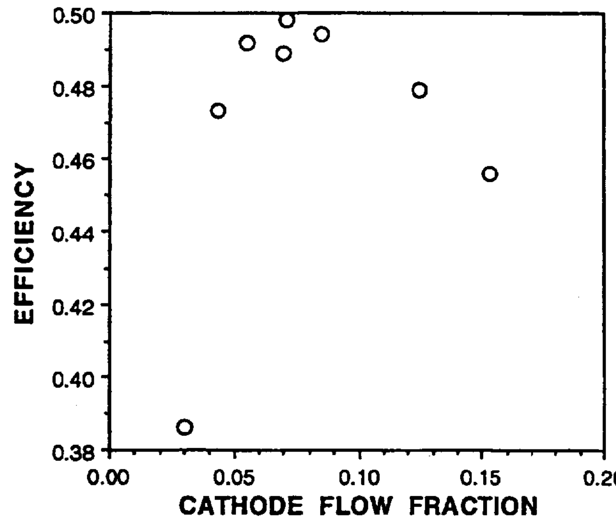


Figure 18.—Effect of cathode flow fraction on efficiency. Thruster voltage of 300 V and discharge current of 4.5 A. (Test segment 3).

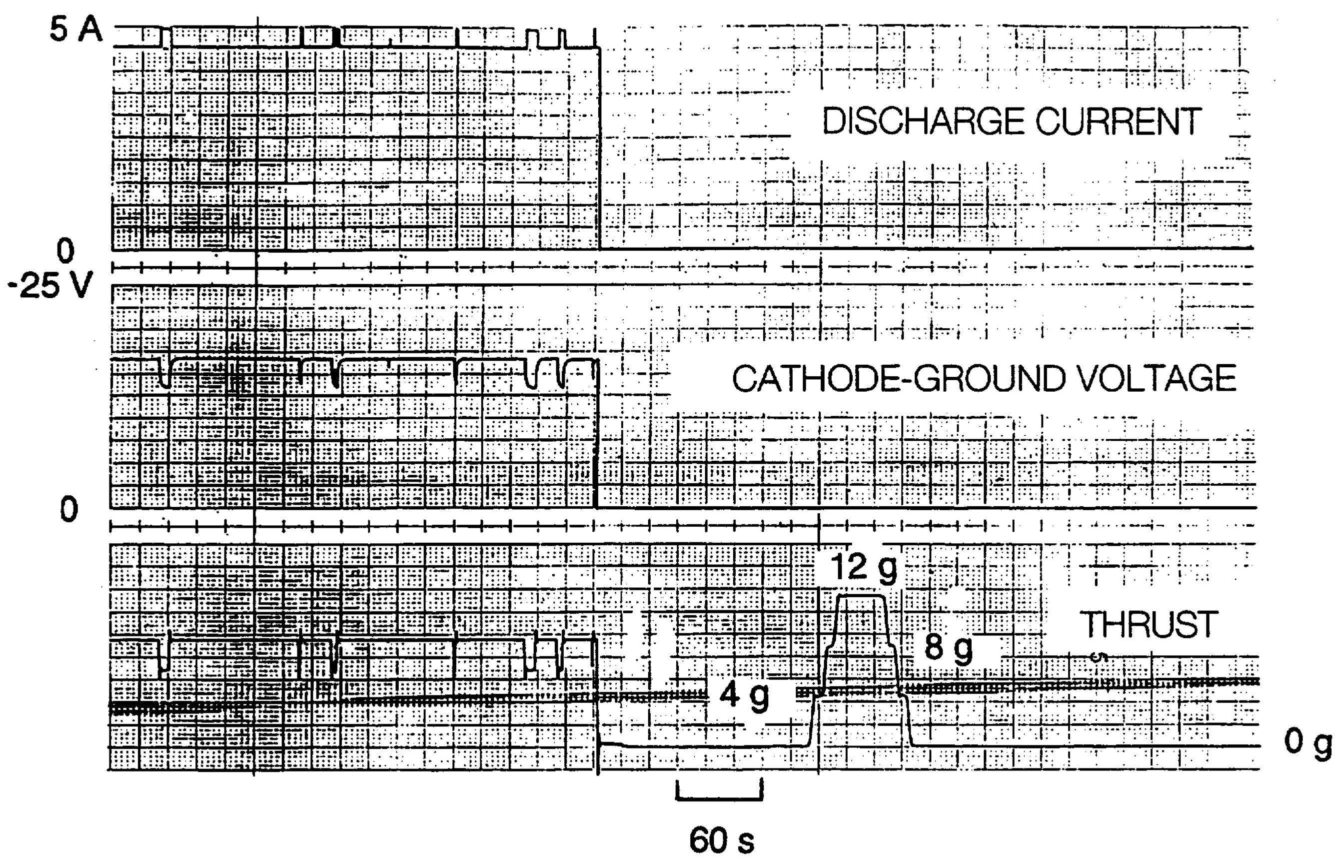
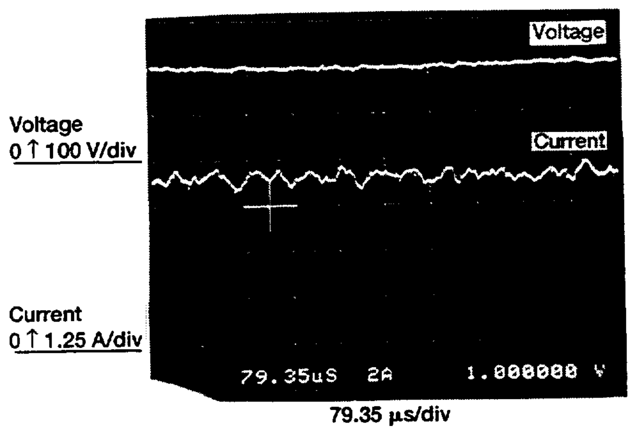
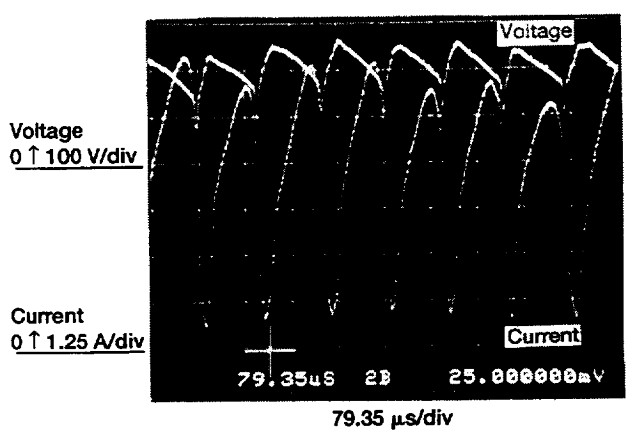


Figure 19.—Strip chart recording showing effects of current instability on thrust and cathode-ground potential. (Test segment 5).



(a) Stable operation.



(b) Unstable mode.

Figure 20.—Oscilloscope photographs showing two modes of thruster operation. (Test segment 5).

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John M. Sankovic, John A. Hamley, and Thomas W. Haag

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13. ABSTRACT *(Maximum 200 words)*

Performance measurements of a Russian flight-model SPT-100 thruster were obtained as part of a comprehensive program to evaluate engineering issues pertinent to integration with Western spacecraft. Power processing was provided by a US Government developed laboratory power conditioner. When received the thruster had been subjected to only a few hours of acceptance testing by the manufacturer. Accumulated operating time during this study totaled 148 h and included operation of both cathodes. Cathode flow fraction was controlled both manually and using the flow splitter contained within the supplied xenon flow controller. Data were obtained at current levels ranging from 3 A to 5 A and thruster voltages ranging from 200 V to 300 V. Testing centered on the design power of 1.35 kW with a discharge current of 4.5 A. The effects of facility pressure on thruster operation were examined by varying the pressure via injection of xenon into the vacuum chamber. The facility pressure had a significant effect on thruster performance and stability at the conditions tested. Periods of current instabilities were noted throughout the testing period and became more frequent as testing progressed. Performance during periods of stability agreed with previous data obtained in Russian laboratories.

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